Mine-induced Sinkholes Over the U. S. Strategic Petroleum Reserve (SPR) Storage Facility at Weeks Island , Louisiana: Geologic Causes and Effects

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ABSTRACT

The initial sinkhole at the Weeks Island SPR site that was first observed in May 1992 gradually enlarged and deepened, concurrent with the increasing dissolution of salt over the mined oil storage area below. Beginning in 1994 and continuing to the present, the injection of saturated brine directly into the sinkhole throat some 76 m (250 **ft)** beneath the surface essentially arrested further dissolution, buying time to make adequate preparation for the **safe** and orderly **transfer** of crude oil to other storage facilities, This mitigation measure marked the first time that such a control procedure had been used in salt mining; previously all control has been achieved **by** in-mine and surface grouting.

A second and much smaller sinkhole was **first** noticed in early **1995** on an opposite edge of the SPR mine, but with a very similar geological and mine mechanics setting. Both sinkholes occur where the edges of upper -152 **m (-500 ft)** and lower -213 m (-700 **ft)** storage levels are nearly vertically aligned. Such coincidence maximizes the tensional stress development, leading to fracturing in the salt Such cracking takes years to develop, perhaps 20 or more. The cracks then become flowpaths for brine incursion, wherein after time it is **released** into mined openings. Undersaturated ground water gradually enlarges the cracks in salt, leading to further dissolution and eventual collapse of the overlying sand to form sinkholes. Other geologic conditions may have been secondary factors in controlling both mining extent and sinkhole location.

An en echelon alignment of sinkholes over other mine edges has been observed. Thus most likely areas of future occurrence at Weeks Island are adjacent to the existing sinkholes; surface inspections are now concentrated at those locations. Although neither timing nor location is predictable with precision, the study of numerous sinkholes elsewhere shows that progression is inevitable, provided that relevant conditions and enough time exists for development. These principles should provide mine designers and operators the knowledge to minimize the occurrence of sinkholes, and to plan for their progression when they occur.

INTRODUCTION

A sinkhole measuring 11 m (36 **ft)** across and 9 m (30 **ft)** deep was first observed in alluvium overlying the Weeks Island, Louisiana, salt dome in **May** 1992, but it was already about a year old, based on initial surface appearance and subsequent reverse extrapolation of growth rates.

A second and much smaller sinkhole was identified in early 1995, nearly three years later. Their positions directly over the edges of the SPR oil storage chamber, a former room-and-pillar salt mine, caused apprehension. The association of sinkholes over mines is well established and this occurrence suggested that groundwater **influx** was **causing** salt dissolution at shallow depth, and associated collapse of soil at the surface. Leaks of groundwater into other salt mines in Louisiana and elsewhere led to flooding and eventual abandonment (Coates et al., 1981). Consequently, much **atten-**

tion has been and continues to be given to characterizing these sinkholes, and to mitigation. This paper summarizes current engineering geologic concepts, and briefly describes diagnostic and risk mitigation efforts being conducted by the U. S. Department of Energy, operator of the Strategic Petroleum Reserve (Bauer et al., 1994).

LOCATION, OCCURRENCE, AND CHARACTERISTICS

The Weeks Island salt dome is located 23 km (14 mi) south of New Iberia, Louisiana, and is the central dome in the Five Islands chain, along with Belle Isle, and Cote Blanche, Avery, and Jefferson Islands. All five have been mined because of their near-surface salt, and their logistical advantage near the Gulf of Mexico and the Intracoastal Waterway. Belle Isle and Jefferson Island are now closed to mining because of deliberate and inadvertent flooding, respectively.

The sediment cover at Weeks Island consists of deltaic alluvium of the ancestral Mississippi River and is about 56 m (185 ft) thick over the top of salt, which is 30 m (100 ft) below sea level at the sinkhole. The water table conforms generally with sea level over the dome but fluctuates somewhat with topography and frequent torrential rains.

Weeks Island sinkhole #1 occurred over the southern perimeter of the Upper Level of the two-level SPR mine (Figure 1), which has contained 73 million barrels of crude oil since 1981. The mine was originally opened in 1902 and salt was extracted commercially until 1977, at which time Morton Salt developed a new mine immediately adjacent to the northwest while the older workings were converted for oil storage. Minor leaks of water had been noted at various times during the 75 years of active mining, but in-mine grouting controlled inflow (Acres, 1987).

The nearly vertical sidewalls in the surface sediments surrounding the sinkhole caused some perplexity initially, but were readily explained geologically as being typical of the Pleistocene loess mantle which caps the island. The sinkhole was also directly beneath a former residence of the now dismantled townsite of the Morton Salt Company, but this history appears unrelated to the sinkhole origin

The relatively small size of the initial sinkhole and lack of diagnostic evidence linking it to the SPR mine caused little concern at first, Sinkholes have formed at other mines in domal salt (Neal, 1994), and they also may occur as a result of natural processes (Autin, 1984). The location near both the edge of the dome and anomalous features in the salt stock including a salt valley, suggested an entirely natural origin was possible (Neal, et al., 1993), although Martinez (1992) insisted from the very beginning that mine-induced factors were likely involved. During the original mining, black salt, gas blowouts, and minor brine seeps were noted beneath the vicinity where the sinkhole developed, and Magorian (1987) later mapped a shear zone just south of the mine boundary. The latter effectively may have influenced the southerly extent of the original mining.

A watch and wait position was adopted, and in March 1993 fluoroscein dye was placed in the sinkhole as a means of detecting connections with the underground mine, or to the surface downdip of the sinkhole. But by mid-1993 it was apparent that the sinkhole was deepening, and monitoring data suggested that the brine influx into the mine was increasing. The evidence for increasing dissolution caused sufficient concern by late 1993 to initiate more detailed diagnostic study, in addition to engineering planning to address actions to decrease the risk of continued oil storage, and/or relocating the inventory to other sites. Safety concerns also necessitated filling the sinkhole with sand as its depth of more than 12 m (40 ft) and location 15 m (50 ft) from the main access road had become hazardous.

As plans to move oil were being formulated in early 1995, a second and smaller sinkhole was identified on the northwest boundary of the mine in a similar geologic and stress-field environment that was seen in the first sinkhole. While the second sinkhole was only 4.3 m wide and 3 m deep (14 and 10 ft), its occurrence confirmed the progressive development of processes causing them and the necessity of expedient mitigation.

SINKHOLE DIAGNOSTICS

A combination of geophysics, drilling, and hydrologic studies were undertaken in 1994 to provide decisive information needed to establish appropriate action and schedules, consistent with perceived environmental risks. In addition, salt mechanics modeling and solutioning processes were studied analytically to complement the field data. A variety of geophysical methods were employed to gain diagnostic information but met with limited usefulness.

Seismic reflection profiling identified an apparent deflection in the reflector near the sinkhole center that at first was thought to be a hydrologic cone of depression (Neal and Myers, 1995). Later detailed study showed this reflector was more apt to represent a structural or material discontinuity. But the perceived anomaly led the way to obtain detailed data that showed a very flat piezometric surface near sea level within highly permeable sediments of the ancestral Mississippi River delta.

Cross-well seismic tomography was conducted across the throat of the sinkhole through four wells constructed in opposite quadrants outside the sinkhole, The velocity tomograms showed a distinct low-velocity zone typical of saturated sediments below the surface sinkhole but failed to reveal detailed throat geometry. The borehole locations in competent high-velocity salt confirmed an essentially vertical sinkhole stmcture at depth (Harding, 1994).

Self potential (SP) surveys that showed hydrologic streaming potential at another mine sinkhole locality were attempted at Weeks Island, Although apparent anomalies were measured near the sinkhole, their interpretation was uncertain, but thought to show downward hydrologic flow along a planar sheet.

Gus mapping of trace hydrogen and methane was conducted to test connectivity with the SPR mine or with anomalies within the salt. Although some anomalous areas around the sinkhole were observed, they did not reveal definitive diagnostic information (LSU, 1994). Further evaluation of gas mapping methods are continuing, as later tests showed evidence of anomalies along mine edges, and near anomalous zones (Camey et al., 1995).

Slanthole drilling directly into and below the sinkhole provided the most direct confirmation of dissolution geometry as evidenced by the drilling of boreholes BH-7A and BH-9 (Figure 2). ***Slanthole BH-9***, adjacent to the sinkhole, was drilled at a high-angle approach directly over the top of the subsurface extension of the surface sinkhole expression. It extended below the top-of-salt elevation encountered in the tomography holes. This wellbore provided the opportunity in July 1994 for injection of rhodamine dye directly into the throat of the sinkhole at -80 m depth, in addition to fluorescein placed in the surface sinkhole in March 1993. The dye, if detected in the fill hole sump, would provide unequivocal evidence of hydrologic connection with the mine. However, neither dye has yet to be detected in the mine, even after more than 30 months of monitoring. Dye dispersion calculations predicted that it could take a year or more to reach the sampling point (Linn and Hinkebein, 1994), possibly explaining the lack of detection of the introduced dye.

Slanthole BH-7A started at 60° inclination and was aimed at the sinkhole throat within the salt at depth. It penetrated the top-of-salt at the normal depth of 185 feet (-56 m) and then continued on through salt into a major sand-filled void at least 22 m (72 ft) deep and 2 m (7 **ft)** wide A 3-D ***hydrologic flowmeter*** was installed in the sinkhole throat and operated for two weeks **(Bauer** et al., 1994; Ballard, **1995a,** b). **The** data indicated essentially vertical flow down the throat, at 0.3 m **/** day. The 3 cm **(~1** in) per day downward movement of the flowmeter itself also indicated that sediment was moving down the throat, presumably in response to dissolution of salt by **undersaturated** groundwater at some point below. This **borehole** also enabled the injection of more dye.

Slanthole EH-1, at 90" to **BH-7A,** transected a 5.5 m (18 ft) sand-filled void at about the same depth, **further** defining a cross-section elongated in ***the*** direction of ***the mine boundary. Slanthole EN-2*** between EH-1 and 7A did not enter the void , even after several **offset** attempts. ***Slanthole EH-3*** intersected the void from the opposite (east) side, with lateral dimensions of 15 and 10 **ft** at two **different** depths, The drilling indicated a very irregularly shaped dissolution feature, but with essentially vertical dimensions directly below the sinkhole. Sand samples recovered **from** the sinkhole throat in EH-1 and **BH-7A** showed concentrated rhodamine dye saturation. Even though throat sand samples recovered from EH-3 and EH-3 sidetrack **#1** showed no dye saturation, it was determined to be hydraulically connected based on flowmeter response in **BH-9, 90 ft** (27.5 m) above, during attempts to place a **flowmeter** below in EH-3.

Once the geometry of a deep void or crevasse was **identified,** with direct measurement of downward flow of water, the suggestion was made by Diamond and **Mills** (1994) to ***feed saturated brine*** directly into the throat through **Bore**hole 7A. Beginning in August 1994 and continuing at present, 3-6 gallons per minute are being gravity fed into the throat 22 m (72 ft) below the top of salt. The brine displaces local ground water which is undersaturated brine at the top of salt. Some of the injected brine flows down into the mine, the rest flows up and out of the throat as evidenced by the upward flow recorded in the flow meter. The encouraging result was that subsidence at the sinkhole was arrested, and virtually no additional downward movement of **fill** sand was measurable. In addition, the apparent groundwater depression at the sinkhole, **if it** ever existed, no longer was observable. The brine introduction evidently had stopped the dissolution of salt, but whether this could be a longer-term fix was problematic; a decision was then made to relocate the SPR oil inventory at an early date and by the safest means.

The construction of a **freezewall** to arrest the flow of ground water into **primary** Sinkhole **#1** began in mid 1995 and was completed by the end of the year. This involved the construction of 56 wells in three circumferential rings around the sinkhole which were used for circulating the **refrigerant.** Testing of the wall in late 1995 was expected to provide reasonable confirmation that a hydrologic barrier had been achieved.

CAUSAL, FACTORS

Unlike other mines where leaks can be observed underground, SPR must rely on indirect evidence such as changes in the oil/water or oil/air interfaces, increased pressure, or changed isotopic composition of the contained water (-750,000 barrels or 1.2 x **10^5 m^3),** about one percent of the total volume. **Thsee** diagnostics are complicated by salt creep closure, which gradually reduces the storage **volume** by **one-fifth** of one percent per year (-160,000 barrels; 2.5 x **10^4 m^3),** a very **small** amount overall, but a ***large*** amount relative to the few gallons per minute leaks that could explain the sinkhole.

Water inflow into the mine was suggested by increasing amounts of brine which were measurable in the fill hole sump. While not a precise measurement, in early 1994 the inflow trend increased from one to nearly three gallons per minute. This increase was noticed almost immediately following filling of the sinkhole with sand; continued deepening of the sinkhole began occurring, at a rate of about 1.5 m^3 (2 yds^3) per day, requiring new fill weekly. This suggested that dissolution was ongoing, and there was reasonable correlation with the amount of increasing brine that was observed in the fill holes and the increasing sinkhole volume.

Brine ***hydrochemistry*** is frequently **analyzed** in salt mines to distinguish meteoric water from connate water. At Weeks Island a decided change in isotopic composition was evident in comparing 1993 water **from** the **fillhole** sump with that obtained in late 1991, about the same time postulated for the sinkhole origin **(Knauth,** 1994). Although inconclusive, earlier isotope trends suggested that a smaller leak may have existed as early as 1987. We do not know the travel time for water through the mine and into the fill hole sump; thus considerable uncertainty remains.

Magorian (Acres, 1987) mapped a shear zone just south of the mine edge, based on external dome structure, surface topography, and gas outbursts experienced during mining. Recent coring in salt during construction of a **freeze-**wall around Sinkhole **#1** also showed shearing and fracturing at depths near -61 m (-200 **ft).** Magorian's mapping of the top-of-salt also showed that both sinkholes are situated in the center of troughs or valleys (Figure 3) having relief of 15 m (50 **ft).** These troughs may reflect boundaries of differential motion of separate segments in the salt stock, although the salt topography is based on old drilling data of questionable reliability.

Anomalous zones, including shear zones, occur frequently in Gulf Coast salt **stocks,often reflecting** differential movement of separate lobes or spines of salt and incorporating a variety of distinctive (anomalous) salt features and/or geologic conditions (Kupfer, 1990; Neal, et al., 1993). Kupfer believes that three or more of these features should occur in combination to be **labelled** anomalous zones. At Weeks Island the geology has several distinctions at and near the **sink-**hole(s) that may indicate it is near an anomalous zone, even though exploratory and **freezewall** drilling reported few impurities that would directly suggest anomalous salt, e.g., coarse crystalline texture (Lock, personal communication, 1995).

The southern mine boundary was apparently influenced by the nearby intersection of anomalous salt features, specifically gas outbursts, brine seeps, and black salt The occurrence of linear gas outbursts experienced during mining does not by **itself** support an anomalous zone designation according to Kupfer (Neal, **1993),** but it appears that their orientation is a non-random process. Thoms and Gehle (1995) indicated a zone of black salt., an anomalous feature, was mapped during mining near the location of the sinkhole. Brine seeps were also mapped near the subsequent sinkhole location, and although at the time judged not meteoric in character, the brine chemistry showed some deviation from normal connate analyses (Martinez, 1995).

Thoms and Gehle (1995) suggested that an association of factors may be responsible for sinkhole formation at **Weeks** Island. In addition to the very **localized** mining-induced stresses adjacent to underground openings that create a ***disturbed rock zone,*** there are additional influences that may work together to localize the initial sinkhole on the southern ***edge*** of the mine. ***Horizontal extension zones*** result from subsidence over the mine and extend beyond the perimeter, leading to dilatancy and eventual fracturing over ***time. Anomalous zones*** are often more prevalent near the edges of salt stocks and are one element of ***susceptible salt zones,*** which may include a variety of local geologic conditions. **Thoms** believes the association and combination of these elements at Weeks Island probably produced ***leak prone areas*** and thus the sinkhole(s).

Rock mechanics modeling in two dimensions by Ehgartner (1993) showed that the areas near the mine perimeter would be in tension and that **fractures** in the top of salt could have formed as early as 1970 **(Figures 4, 5). The cracks** initiate at the top of salt and grow toward the mine because of bending and stretching of the salt as a result of creep closure. Such cracks could be exposed to undersaturated **ground** water and gradually enlarge at the same time the crack was extending toward the mined openings. Sampling of subsurface water shows brine is undersaturated at distances greater than 4-5 feet above the top of salt The modeling results established a reasonable mechanism for eventual incursion of groundwater and are also validated by surface survey data showing subsidence over the mine, which is in close agreement with values from Ehgartner's modeling.

This mechanism was **verified** using a 3-D model developed by **Hoffman** (1994). His analyses predicted tensile zones similar to Ehgartner's **2-D** model, particularly over the vertically-aligned edges of the upper and lower mine levels. In addition, a dilatant ***zone*** **(Figure 6)** was predicted, using a criterion developed **from** previous rock **mechanics** tests on Weeks Island salt by Ehgartner **(1994). The dilatant** zone was predicted to extend **from** the top of salt to the edges of the mine. **Dilatancy** is characterized by increased porosity, hence permeability, caused by **microfracturing.** Thus the **time**-dependent mine subsidence results in tensile and dilatant zones that potentially explain the groundwater incursion into the mine. With both sinkholes occurring almost exactly over aligned levels of the mine, the mechanisms explained above are credible, independent of the presence of anomalous geologic features.

The deviations from "normal" geologic conditions noted above by Thorns seem to support the notion of ***susceptible salt zones*** influencing sinkhole development at the initial location. However, no sinkholes have been observed along the east boundary of the mine (also **a zone** of gas outbursts, etc.). Thus the primary causal factor is most likely the mechanics associated with mine subsidence.

CONTINUING EFFECTS AND SINKHOLE PROGRESSION

The processes of subsidence and fracturing caused by continuing salt creep around the mined openings will continue indefinitely, Once the mine is filled with saturated brine, as closure plans now assure, there will be less **opportunity** for further sinkhole development. However, additional sinkhole development seems likely within a few years if the mine is left at atmospheric pressure, even though the time or location is not predictable.

The injection of brine into the throat and concomitant slowing of dissolution has altered the natural hydrologic environment in **significant** ways. Had this not been accomplished, the sinkhole growth rates **would have progressed** (Russo, 1994). The risks of sinkhole collapse have been calculated in other areas on the statistical basis of collapses vs area vs frequency (Beck, 1991). Such analyses are not appropriate for Weeks Island, but the very existence of the second sinkhole **confirms** the continuing progression of sinkhole development.

Hindsight is often **20/20,** but an earlier leak in late 1978 in an area known as the "Wet Drift" might have been a forewarning of events to come (Acres, 1987). Although in-mine and surface grouting ***readily*** controlled the leak at the time, it could just as easily have gone to an uncontrollable state, and formed sinkholes then, had the appropriate mitigation steps not been taken. The location of that occurrence was also very near the coincident upper and lower mine boundaries; in a sense, the two existing sinkholes are actually events two and three.

As the progression of sinkhole causative factors seems inevitable, and risks of surface collapse increase with the mine empty, the plan implemented by DOE in late 1994 involved the construction of a **freezewall** around the principal sinkhole that was demonstrated to be leaking into the **mine** at a known rate. The **freezewall** is intended to form a hydrologic barrier that will limit hydrologic inflow and control further dissolution. The oil will then be drawn down before filling the mine with brine **and** permanently sealing the accessways and piping systems. During this relocation process, which began in November 1995, concerted efforts to **identify** the formation of new sinkholes are being made by quarterly inspections at the surface.

SUMMARY AND CONCLUSIONS

- The limits of the original mining at Weeks Island were controlled partly by geological factors, including a variety of anomalous features: gas outbursts, shear zones, sand, oil seeps, black salt, and brine incursions.
- Mining terminated along a planar zone characterized by gas outbursts, black salt, and brine seeps. The two level mine produced a stress state conducive to bending and stretching as a result of salt creep toward areas of lower stress. The bending and stretching likely caused the cracks to extend **from** the top of salt to the mine in the vicinity of Sinkholes **#1** and **#2.**
- Once established, brine flow through **fracture** pathways eventually produce dissolution voids on the top of salt. Sediment collapse into such voids produced the sinkholes.
- Sinkhole **#1** stabilization has been temporarily effective by injecting saturated brine into the throat. Construction of a **freezewall** around the sinkhole will provide added hydrologic control during **drawdown** and relocation of the oil. Sinkhole **#2** was sufficiently small and not growing as of late 1995 to warrant no additional study or mitigation efforts.

ACKNOWLEDGMENTS

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Figure Captions

Figure 1 Weeks Island salt dome, Louisiana, showing location of the two sinkholes, two fill holes, mined areas, and contours atop the salt stock

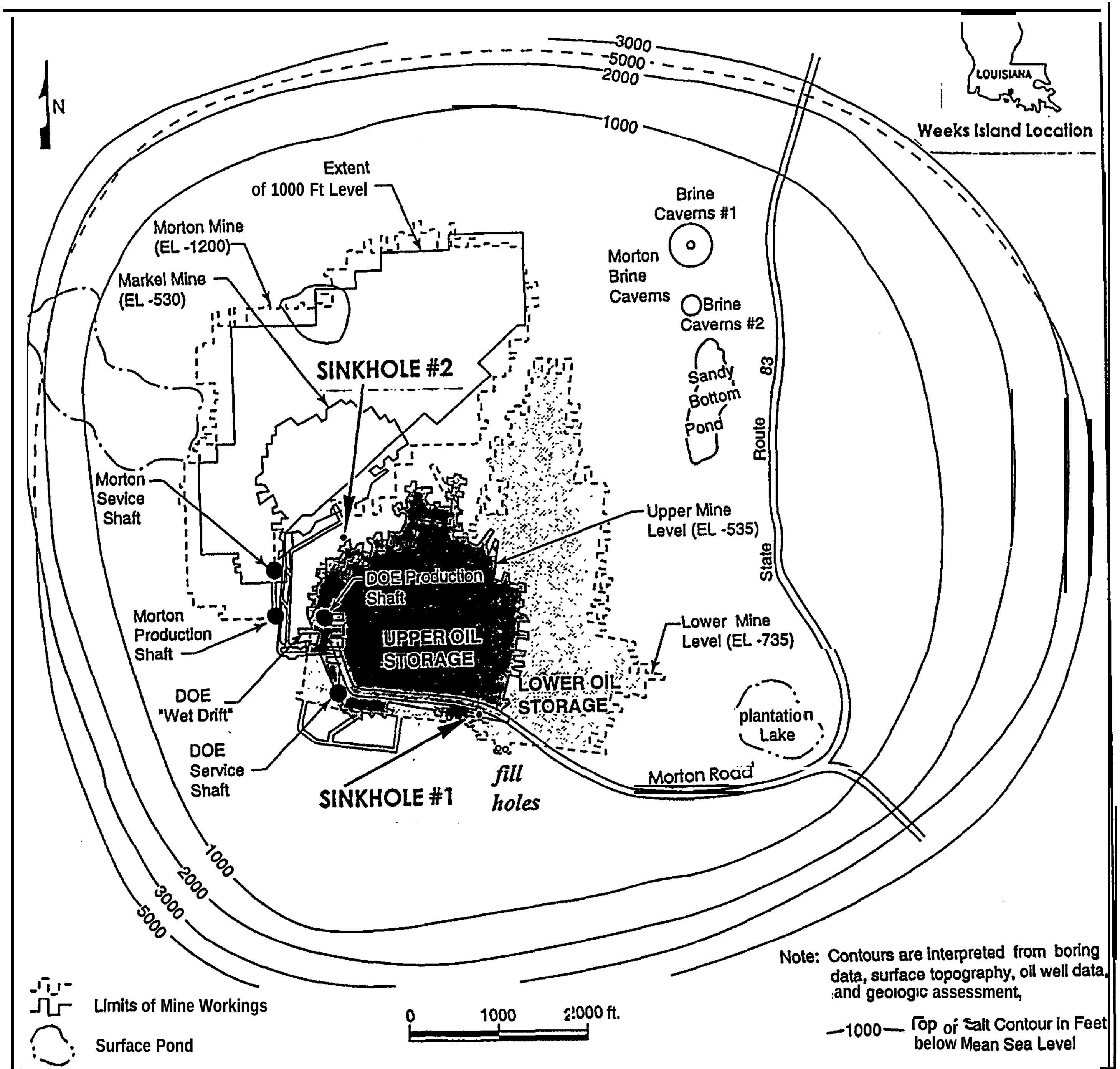
Figure 2 Diagrammatic representation of exploratory drilling and geometry of Sinkhole #1 throat. Boreholes BH-3, 4, 5, and 6 were drilled for crosswell seismic tomography, slantholes BH-7A and 9 were drilled for throat definition. EH-I, 2, and 3 further defined the throat and provided decisive information regarding grouting potential. Accentuated portions of boreholes define throat penetrations.

Figure 3 Top of salt contours with detail over mined openings. Sinkholes 1 and 2 are located in apparent troughs, possibly separating individual lobes or spines (from Acres, 1987; SAND87-7111).

Figure 4 Geomechanical modeling by Ehgartner (1993) and Hoffman (1994) showed mechanism for crack development in tension that would develop over mined openings after a number of years, and progressing through weakened dilatant zones. Largely as a results of this modeling, crosswell tomography was conducted and angled boreholes were planned to intersect such features.

Figure 5 Conceptual development of Weeks Island, Louisiana, sinkholes, based on geomechanical modeling and presumed hydrologic connection with undersaturated groundwater. Sinkhole #1 was first observed in 1992, but likely took years to develop. Progressive enlargement of the dissolution channel was initiated following formation of tension crack(s) ca. 1970, but not manifesting as a sinkhole until about 1990-91. Sinkhole #2 was first observed in early 1995.

Figure 6 Dilatant damage at simulated times corresponding to: 1980 (oil fill), 1994, and 2008. Damage is indicated where D > 1.0.



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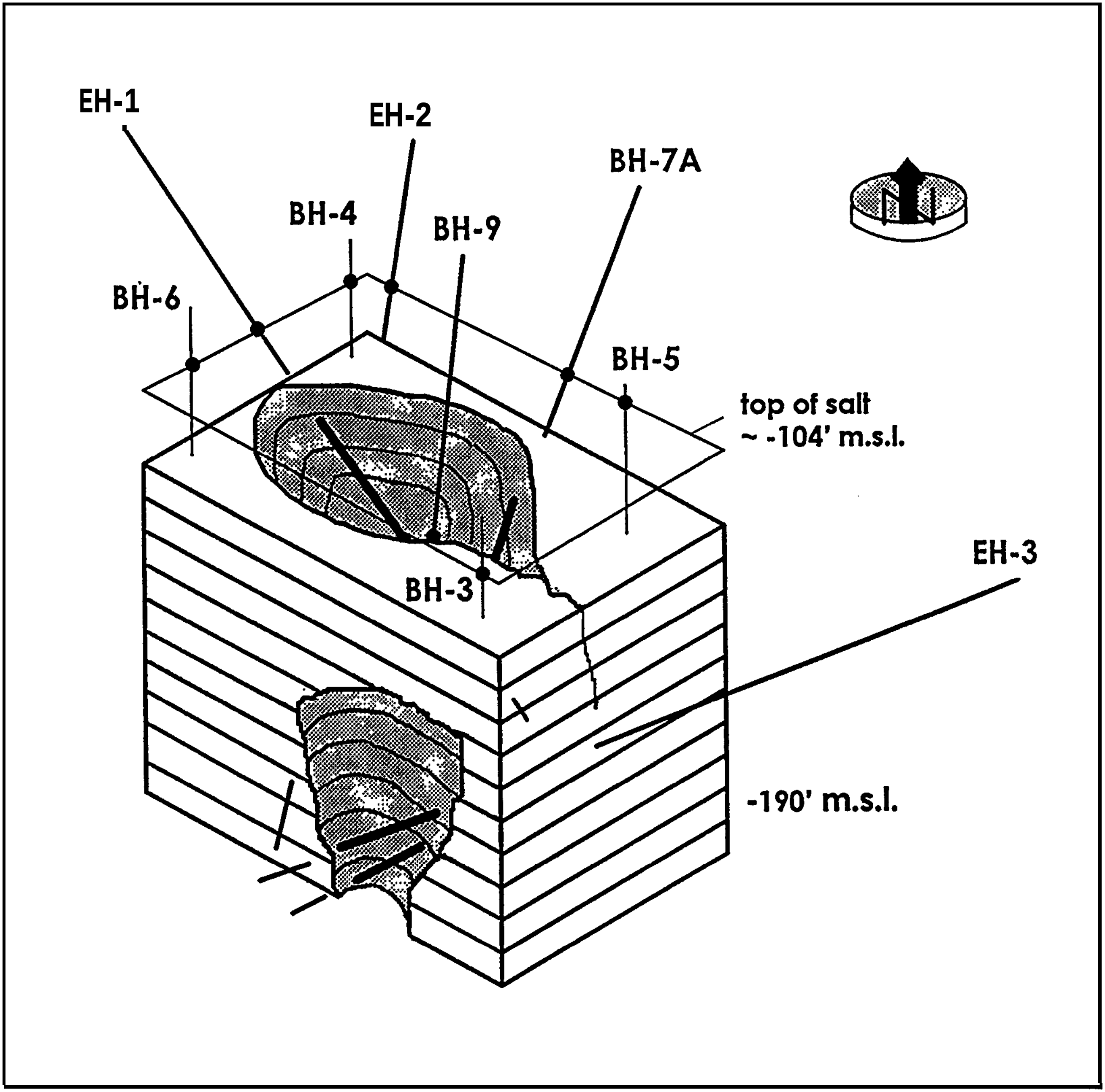

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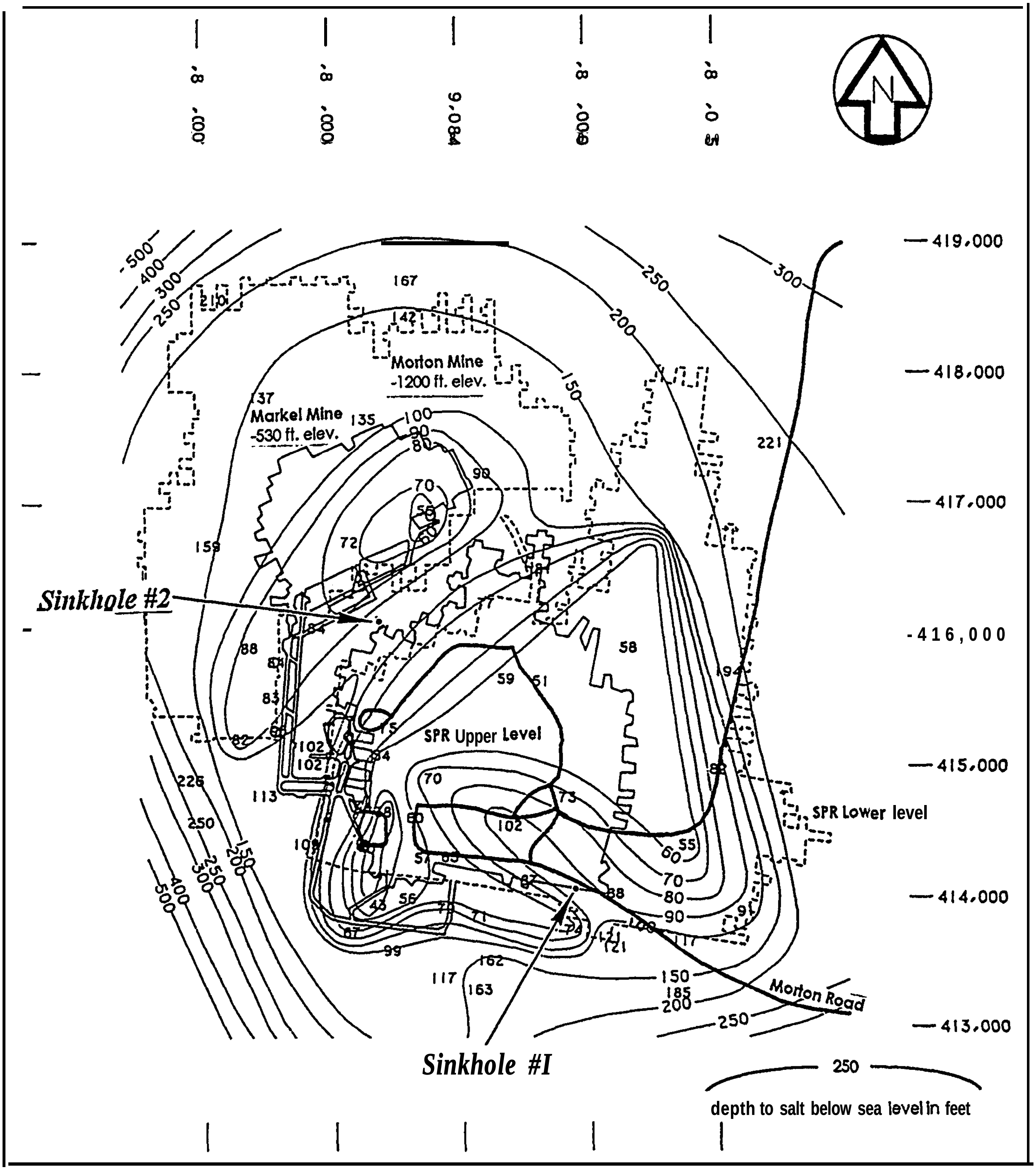

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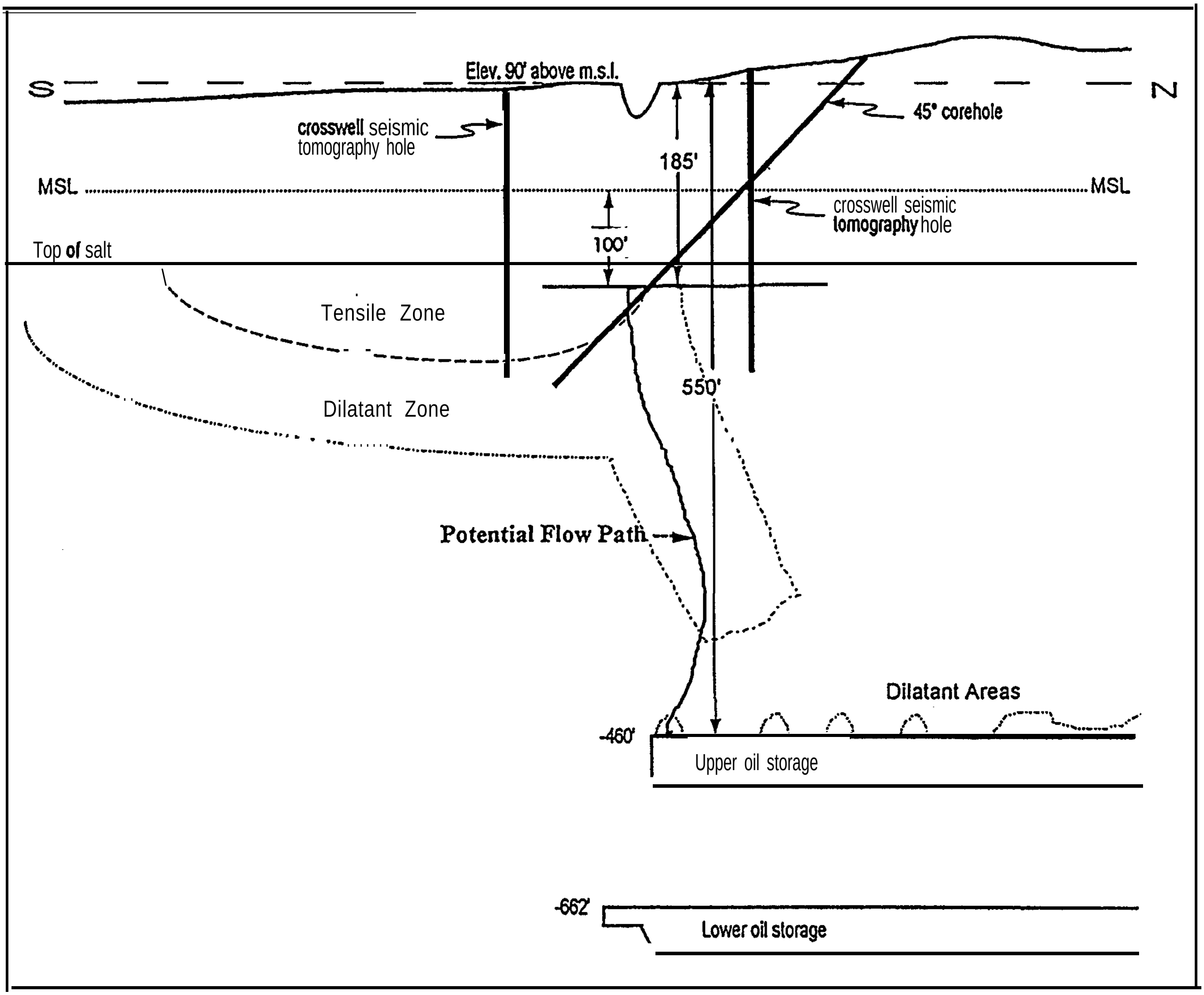

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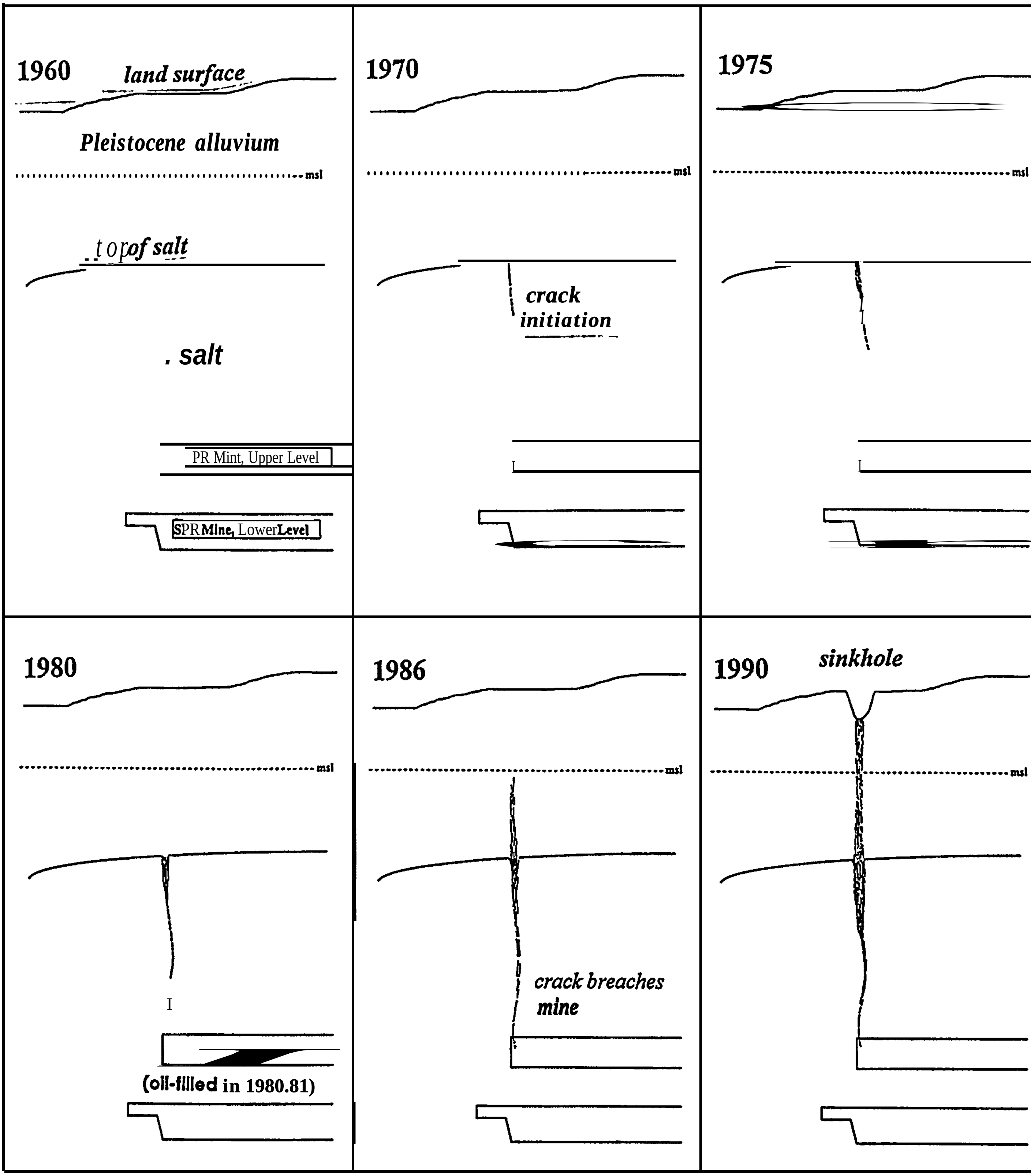

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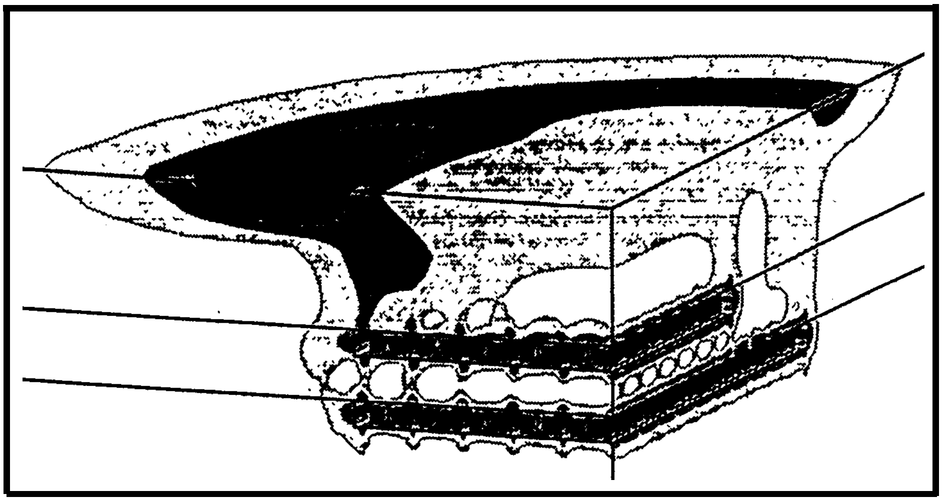
FIGURE 6



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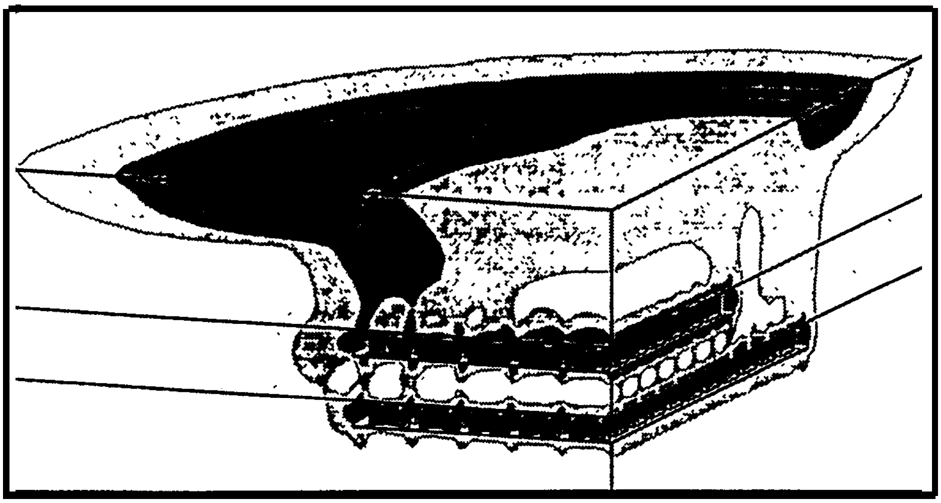
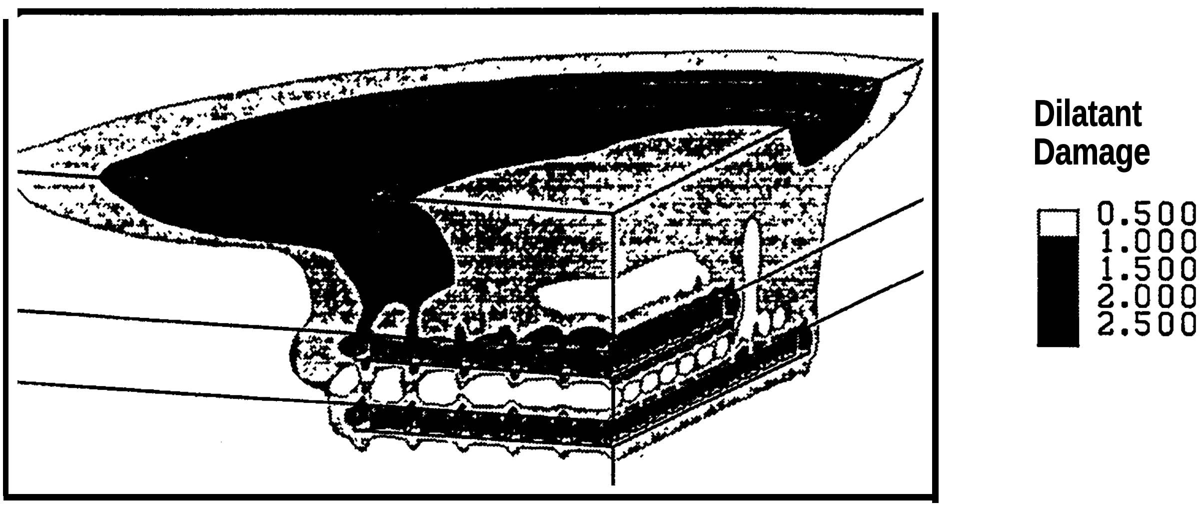


1994



2008

Dilatant damage at simulated times corresponding to: 1980 (oil fill), 1994, and 2008. Damage is indicated where D > 1.0.